International Journal on Science and Technology (IJSAT)

E-ISSN: 2229-7677 ● Website: www.ijsat.org ● Email: editor@ijsat.org

Parameters That Influence the Pore Size of Needle Punch Non-Woven Air Filter Fabrics

Ashwini K[1], Yasotha P[2]

[1]M.Sc. Student, Department of Costume Design and Fashion, PSG College of Arts and Science, Coimbatore

[2]Associate Professor, Department of Costume Design and Fashion, PSG College of Arts and Science, Coimbatore

Abstract:

Indoor air quality has become a major public health concern due to rising concentrations of particulate matter (PM2.5 and PM10), which are linked to respiratory and cardiovascular diseases. The World Health Organization recommends strict limits on PM exposure, increasing the demand for efficient air filtration materials. Needle-punched non-woven fabrics are widely used in commercial air filters due to their cost-effectiveness, mechanical strength, and customizable structure. The pore size of these fabrics—one of the most critical factors governing air filter efficiency—is strongly influenced by manufacturing and structural parameters such as fiber diameter, fabric thickness, bulk density, needle penetration depth, punch density, fiber orientation, and web layering. Increased punch density and deeper needle penetration generally reduce pore size and enhance particle capture. Optimizing these interdependent parameters is essential to achieve a balance between high filtration efficiency, low airflow resistance, and compliance with WHO PM guidelines. This study highlights the key variables controlling pore structure in needle-punched non-woven air filter fabrics and their impact on overall filtration performance.

Keywords: Air pollution, Air filter, Airflow efficiency, Pore size, Needle Punched Fabric, Human Health.

1. Introduction:

Air pollution is recognized as one of the most significant environmental and public health challenges worldwide. According to the World Health Organization, air pollution contributes to millions of premature deaths annually and is linked to respiratory diseases, cardiovascular complications, asthma, and lung cancer. Fine particulate matter ($PM_{2.5}$ and PM_{10}), industrial emissions, vehicular exhaust, and indoor pollutants significantly deteriorate air quality, highlighting the urgent need for efficient air filtration systems. [11, 8]

Air filtration technologies are essential for maintaining safe indoor environments and ensuring clean air in critical applications such as hospitals, laboratories, pharmaceutical facilities, clean rooms, automotive cabins, HVAC systems, and industrial dust collection units. Various filtration mechanisms are employed depending on performance requirements, including mechanical filtration, electrostatic filtration, membrane-based filtration, activated carbon adsorption, and high-efficiency systems such as HEPA filters. Among these technologies, nonwoven filter media have gained substantial attention due to their high porosity, controllable pore distribution, lightweight structure, and excellent particle capture performance. Needle punching is one of the most important mechanical bonding techniques used in manufacturing nonwoven filter fabrics. It is extensively applied in producing pre-filter layers, structural support layers, and substrate materials for advanced filtration systems. Even in high-performance filtration assemblies such as HEPA systems, needle-punched nonwoven fabrics often serve as pre-filtration or reinforcement layers. [8, 10, 13]

A critical performance parameter of needle-punched nonwoven filters is pore size distribution. Pore characteristics directly affect filtration efficiency, airflow resistance, pressure drop, and dust holding capacity. Effective control of structural and processing variables is therefore essential to achieve an optimal balance between filtration efficiency and energy consumption. Proper pore size optimization ensures efficient particle capture while maintaining acceptable pressure drop, particularly in high-efficiency applications. This study focus on analysing the parameters of needle punch non-woven fabric and reduce the pore size to increase the more filter efficiency. [12]

2. Parameter that influencing air filter efficiency

The filtration efficiency of needle-punched nonwoven media is determined by a complex interaction between structural characteristics, fiber properties, and manufacturing conditions. Since needle punching mechanically entangles fibers to form a consolidated web, parameters influencing fiber orientation, compaction intensity, and pore structure significantly affect performance.

The key parameters influencing air filter efficiency include: Pore size, Fabric density, Fabric thickness, Fiber type, Needle punch density, Needle penetration depth, Stroke frequency.

2.1 Pore Size

Pore size is one of the most influential structural parameters in needle-punched nonwoven filtration media. It is primarily controlled by fiber diameter, web density, carding settings, and needling intensity. Increasing punch density and needle penetration depth enhances fiber interlocking and compaction, thereby reducing the mean flow pore size. [1]

The use of finer fibers significantly reduces pore dimensions while increasing the specific surface area available for particle capture. Optimized carding parameters further contribute to uniform pore distribution and improved filtration efficiency. Similarly, increasing fabric density decreases average pore size and enhances particle retention performance. [2, 9]

However, pore size reduction introduces a trade-off between filtration efficiency and pressure drop. Smaller pores improve particle capture but increase airflow resistance. Therefore, filter design must identify an optimum pore size that ensures high efficiency without excessive energy consumption. [3]

2.2 Fabric Density

Fabric density, defined as mass per unit volume, strongly influences pore structure and permeability. Higher density, achieved through increased punch density, deeper needle penetration, or calendaring, results in tighter fiber packing and reduced porosity.

An increase in density generally decreases pore size and enhances particle capture efficiency. However, this also reduces air permeability and increases pressure drop. [2, 13] Increased punch density compresses the fiber network, thereby lowering pore dimensions and improving dust retention. [3]

Higher volume density reduces permeability due to narrower airflow passages. [4] [13] Thus, density optimization is critical to balancing filtration efficiency and acceptable pressure drop.

2.3 Fabric Thickness

Fabric thickness affects the depth of filtration and internal pore geometry.

As thickness increases:

- The number of internal pore pathways increases.
- Individual pore size tends to decrease due to greater fiber content.
- Mean flow pore size decreases.
- Filtration efficiency improves.
- Air permeability decreases.
- Pressure drop increases.
- Dust holding capacity increases.

Thicker fabrics provide enhanced depth filtration, allowing particles to be captured throughout the structure rather than only on the surface. [2] However, excessive thickness can lead to higher airflow resistance.

2.4 Fiber Type (Polymer Material)

Fiber selection influences mechanical strength, structural integrity, and functional behavior.

Fiber Length & Fineness

- Longer fibers enhance entanglement and strength.
- Finer fibers improve uniformity and bonding.
- Short or coarse fibers may reduce fabric cohesion.

Mechanical Properties

- High-tenacity synthetic fibers increase tensile and tear strength.
- Elastic fibers improve resilience and recovery.
- Strong fibers resist repeated needle penetration damage.

Functional Characteristics

- Coarse fibers increase bulk and permeability.
- Hydrophilic fibers enhance moisture absorption.
- Hydrophobic fibers improve chemical resistance.

Blending natural and synthetic fibers can balance durability, cost, comfort, and filtration performance. [5]

2.5 Needle Punch Density

Needle punch density refers to the number of needle penetrations per unit area (punches/cm^2). Increasing punch density enhances fiber entanglement and web consolidation, improving tensile strength and stiffness.

However, excessive needling may cause fiber breakage and structural damage, reducing elongation and mechanical integrity.

Higher punch density:

- Reduces thickness and bulk
- Decreases pore size
- Lowers air permeability
- Improves filtration efficiency

An optimal punch density is therefore essential to balance mechanical strength and airflow performance. [6, 13]

2.6 Needle Penetration Depth

Needle penetration depth determines the extent of fiber engagement during needling.

- Deeper penetration increases fiber entanglement and consolidation.
- Tensile strength improves up to an optimal depth.
- Excessive penetration causes fiber damage and over-compaction.
- Greater penetration reduces thickness and pore size.

Thus, penetration depth must be carefully controlled to prevent structural degradation. [13]

2.7 Stroke Frequency

Stroke frequency refers to the number of needleboard movements per minute.

- Higher frequency increases fiber interaction and entanglement.
- Mechanical strength improves with controlled increase.
- Excessively high frequency may cause fiber damage if web speed is not synchronized.
- Influences fabric density and uniformity.

Balanced stroke frequency ensures consistent structural properties. [13]

3. CONCLUSION

The deep analysis into various needle punching parameters proves that changes in parameters, has notable changes in fabric consolidation. The pore size of the fabric decreases when needle penetration & punch density fabric thickness increases. As the pore size decreases the filtration efficiency of filter fabric increase along with increased in air permeability. Punch density has greater effect on overall fabric performance. As the punch density increases fabric strength, stiffness increases whereas pore size web compression and thickness decreases.

Among the various air filter fabrics are very important while considering health issues so we conclude indoor air quality play major role to produce environment and also the human health issues.

References:

1. Dixit, Priyal, and S. M. Ishtiaque. "Optimisation of mechanical and functional properties of needle-punched nonwoven filter through fibre denier specific carding parameters." Indian Journal of Fibre & Textile Research 48.3 (2023).
2. Sakthivel, S., Anban JJ Ezhil, and T. Ramachandran. "Development of needle-punched nonwoven fabrics from reclaimed fibers for air filtration applications." Journal of Engineered Fibers and Fabrics 9.1 (2014): 155892501400900117.
3. Naderi, Keivan, Parham Soltani, and Yu Song. "Optimization of needle punched nonwoven filter media for enhanced dust filtration performance." Scientific Reports 15.1 (2025): 31852.
4. Dedov, A. V., V. A. Kuznetsov, and V. G. Nazarov. "Influence of volume density of nonwoven needle-punched fabrics on their permeability and mechanical properties." Fibre Chemistry 51.6 (2020): 440-443.
5. Govindaraju, Rajkumar, and Srinivasan Jagannathan. "Certain properties of needle punched nonwoven fabrics made from silk and wool fibers." Trends Text Eng Fash Technol 1 (2018): 28-31.

6. Kang, Tae Jin, et al. "Effect of punching density on the mechanical and thermal properties of needle-punched nonwoven carbon/phenolic composites." Polymers and Polymer Composites 10.7 (2002): 521-530.
7. Kothari, V. K., A. Das, and A. Sarkar. "Effect of processing parameters on properties of layered composite needle-punched nonwoven air filters." Indian Journal of Fibre and Textile Research 32.6 (2007): 196-201.
8. Bian, Ye, et al. "Influence of fiber diameter, filter thickness, and packing density on PM2. 5 removal efficiency of electrospun nanofiber air filters for indoor applications." Building and Environment 170 (2020): 106628.
9. Liu, Xingcheng, Henggen Shen, and Xueli Nie. "Study on the filtration performance of the baghouse filters for ultra-low emission as a function of filter pore size and fiber diameter." International Journal of Environmental research and public health 16.2 (2019): 247.
10. Jamdagni, R. P., and K. N. Chatterjee. "QUALITY ASPECTS OF NONWOVEN NEEDLE-PUNCHED POLYESTER FILTER FABRICS FOR DUST CONTROL." Natural Sciences and Technology (2014): 14.
11. Yesuf, Hanur Meku, et al. "Super-hydrophobic blended needle-punched nonwovens integrated with silica-aerogels for PM 2.5 filtration." Environmental Engineering Research 30.3 (2025).
12. Anandjiwala, Rajesh D., and Lydia Boguslavsky. "Development of needle-punched nonwoven fabrics from flax fibers for air filtration applications." Textile Research Journal 78.7 (2008): 614-624.
13. Naderi, Keivan, Parham Soltani, and Yu Song. "Optimization of needle punched nonwoven filter media for enhanced dust filtration performance." Scientific Reports 15.1 (2025): 31852.